X-RAY ABSORPTION SPECTROSCOPY AND SCATTERING OF INTERSTELLAR DUST

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MYSTERIES OF ISM DUST

- What is it **made** of?
- What **size** (or **range of sizes**) is it?
- How **dense** is it?
- What **shape** is it?
- **Where** is it?
  - Does it always mix with IS gas?

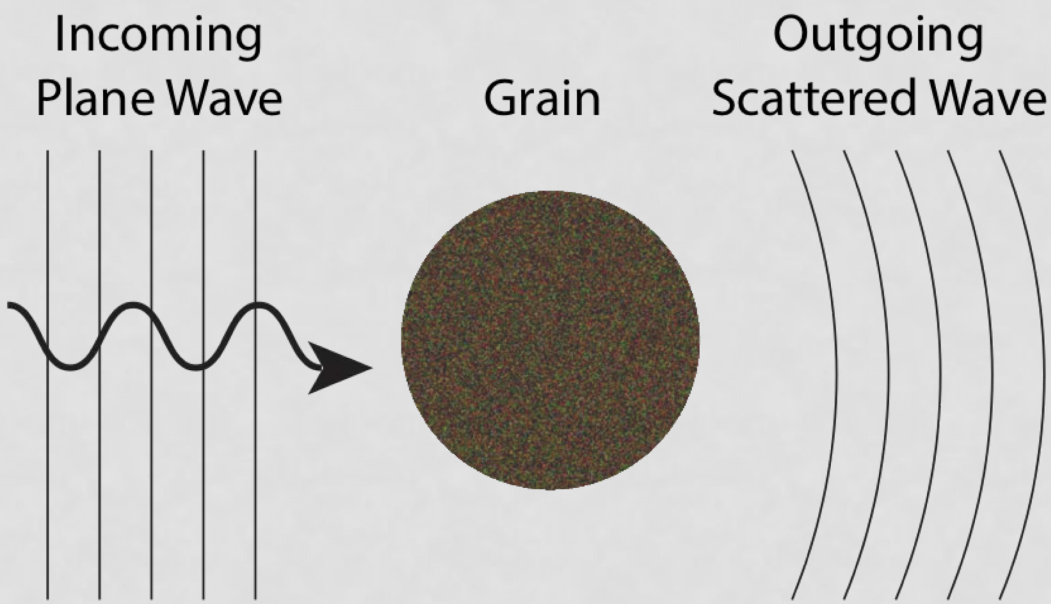
HOW TO STUDY DUST

- Dust both **scatters** and **absorbs** UV, optical, and near-IR light, leading to 'extinction' (A_V)
- Dust **emits** in the 'thermal IR' (~10-100 μm)
- Longer wavelengths less affected (not zero)
- What about X-rays?

WHY USE X-RAYS?

- Pros:
  - Probes the entire grain structure
  - Sensitive to the largest grains – where the mass resides
  - Sensitive to line-of-sight position of grains
- Cons:
  - Small telescopes
  - Poor to moderate energy resolution
  - Faint sources

X-RAY HALOS: PHYSICS



To an X-ray photon, a dust particle is a cloud of *nearly* free electrons.

Each electron oscillates as a dipole at the wave frequency – i.e., Rayleigh scattering.

$$I(r,\theta) = \frac{(1+\cos^2\theta)k^4|\alpha|^2}{2r^2} I_0$$

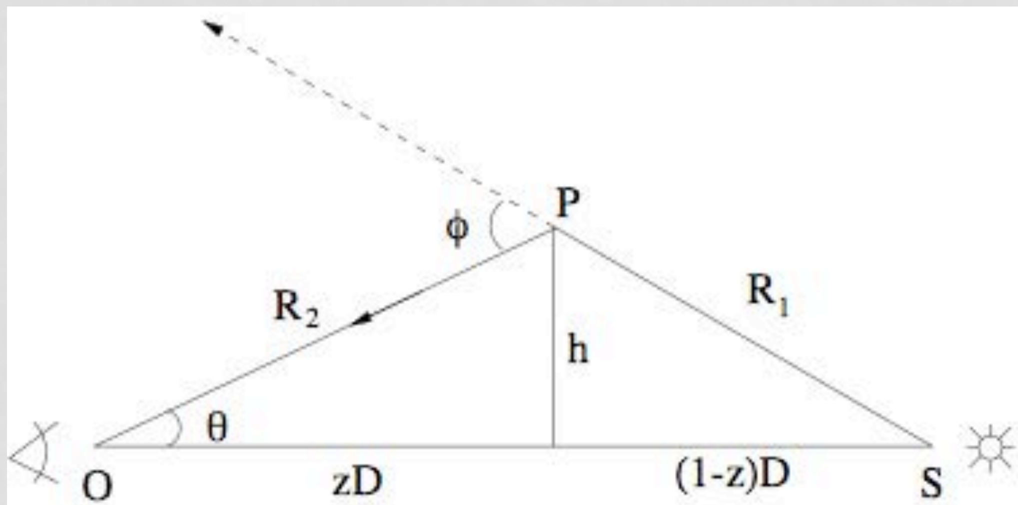
where $\alpha = \frac{m^2-1}{m^2+2}a^3$

X-RAY HALOS: ASTROPHYSICS

$$\frac{d\sigma}{d\Omega}(E,a,\phi) \approx 1.1\Big(\frac{\rho}{3\,\mathrm{g\,cm^{-3}}}\Big)^2 a_{\mu m}^6 E_{keV}^{-2} \exp\Big(-\frac{\phi^2}{2\sigma^2}\Big)\,\mathrm{cm^2sr^{-1}}$$

where $\sigma \approx \dfrac{62.4''}{E_{keV}\,a_{\mu m}}$

To get the observed halo intensity, integrate the scattering over the line of sight:



For D=10 kpc, ϕ = 1' gives a maximum *h* of only 1.5 pc. The scattered x-rays travel along nearly the same line of sight as the direct photons, so:

$$I_{\mathrm{halo}} \propto F_x$$

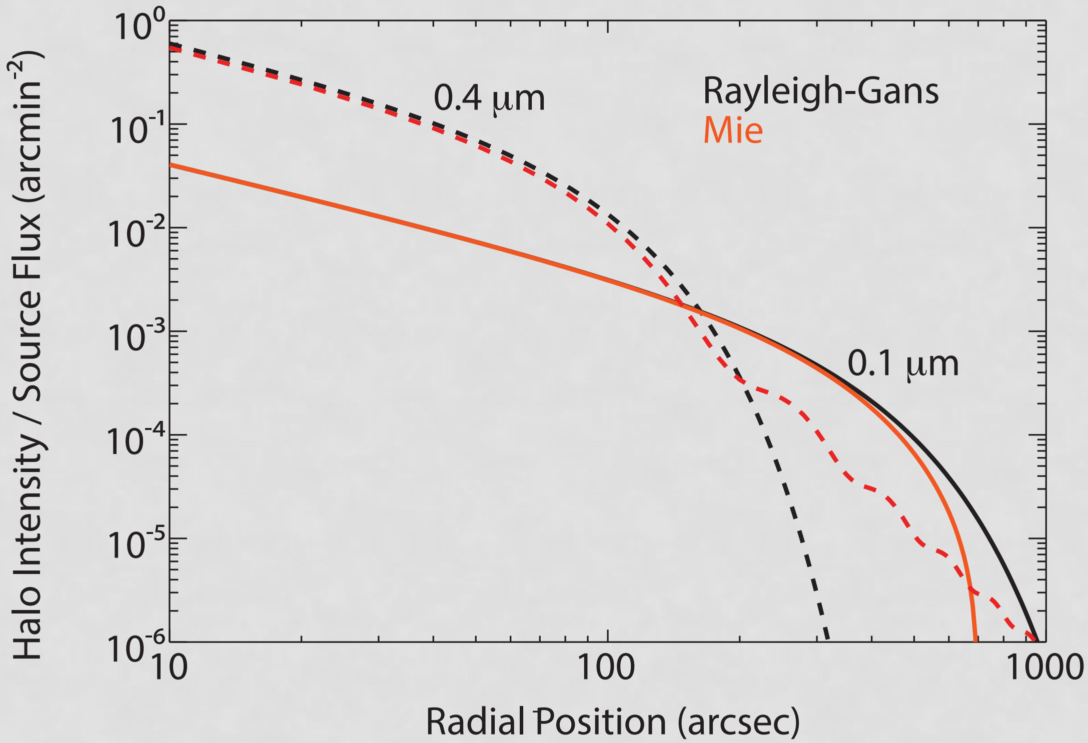
X-RAY HALOS: ASTROPHYSICS

The final answer is

$$I_{sca}(\theta) = N_{\rm H} F_X \int dE S(E) \int da n(a) \int \frac{f(z)}{(1-z)^2} \frac{d\sigma}{d\Omega}(E, a, \frac{\theta}{1-z}) dz$$

where :

- **S(E)** : X-ray spectrum
- **n(a)** : Size distribution of dust grains
- **ρ** : Grain mass density
- **f(z)** : Distribution of dust along line of sight



X-RAY HALOS: ASTROPHYSICS

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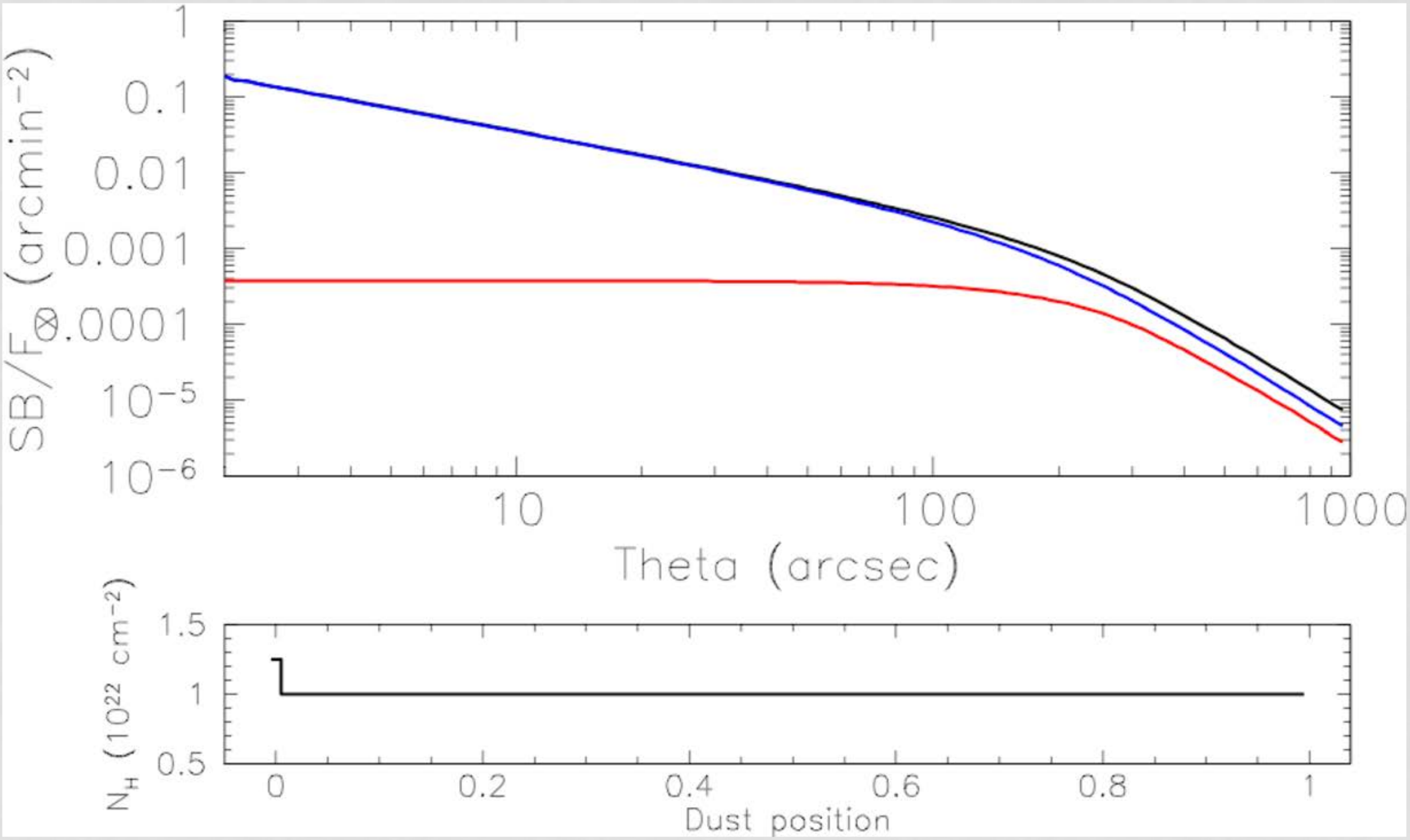
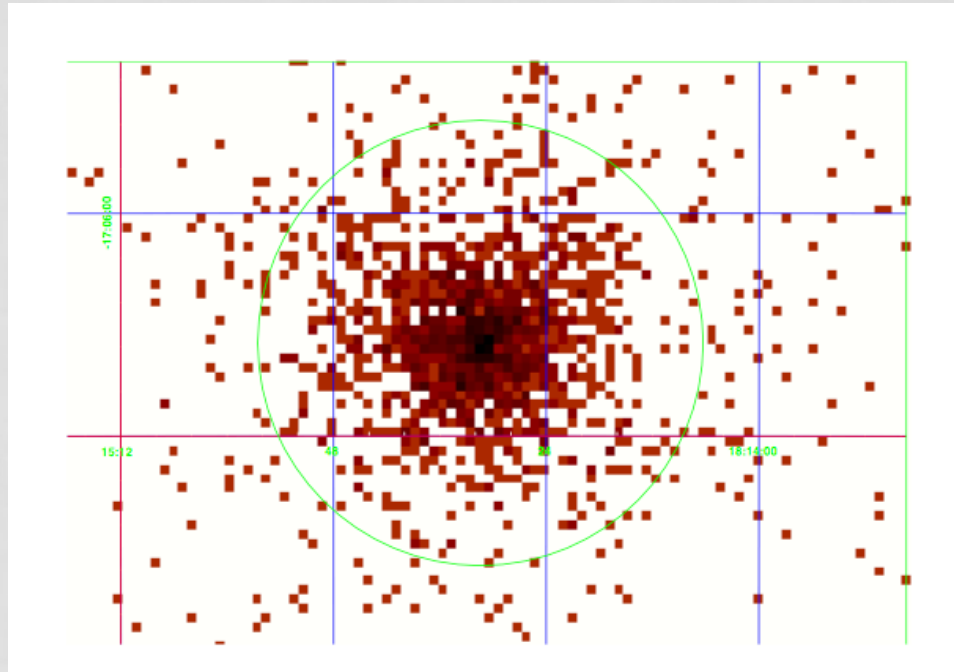


X-RAY HALOS: HISTORY

- First detected with the Einstein satellite
- Predehl & Schmitt (1995) compiled a survey of ~30 halos with ROSAT.
- Despite the strength of the halo in this energy range, analysis is complicated by the limited energy resolution and the many dependent variables.



ROSAT Obs. Of GX13+1, a bright highly-absorbed X-ray binary system

$$\tau_{sca}=0.087 \times A_V(mag) \times E(keV)^{-2}$$

$$N_H[cm^{-2}]/A_V=1.79\times10^{21}$$

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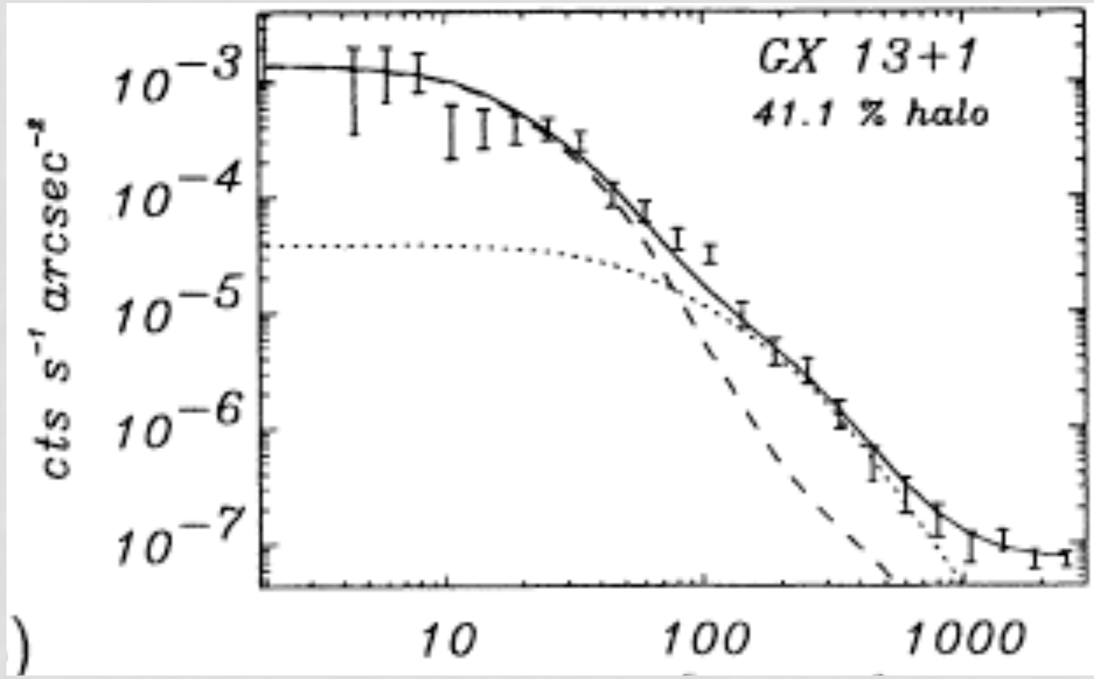

Predehl & Schmitt 1995

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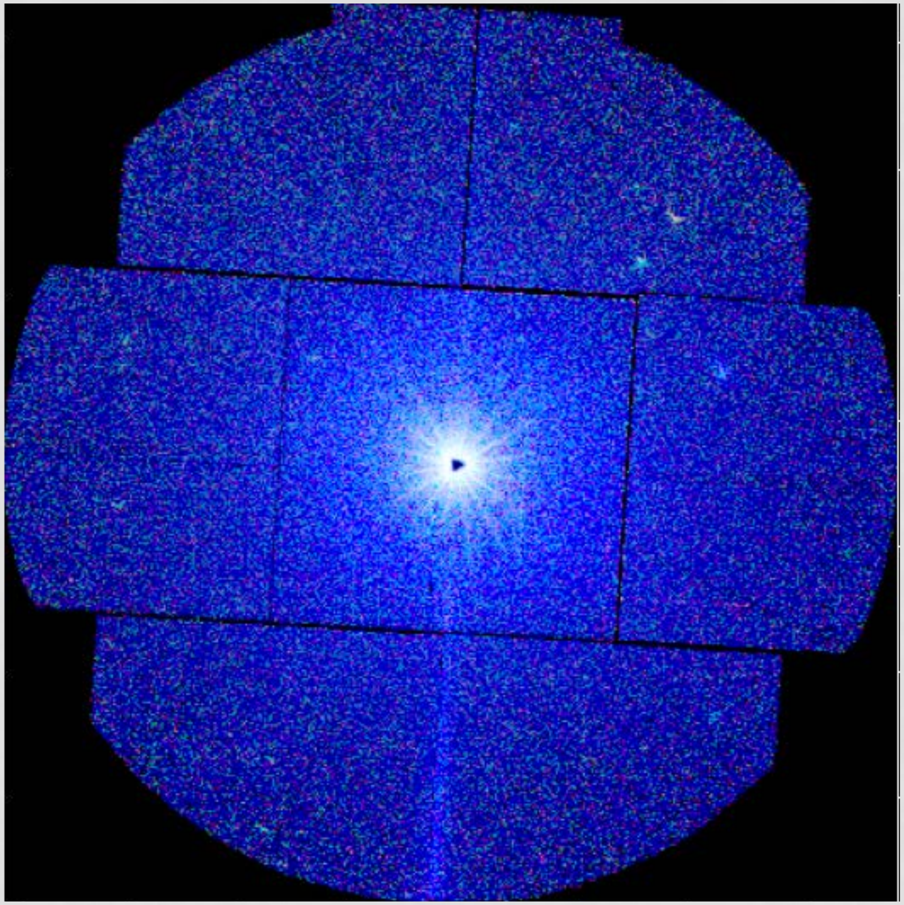
N_H[cm^{-2}]/A_V=1.79x10^{21}

X-RAY HALOS: MODERN

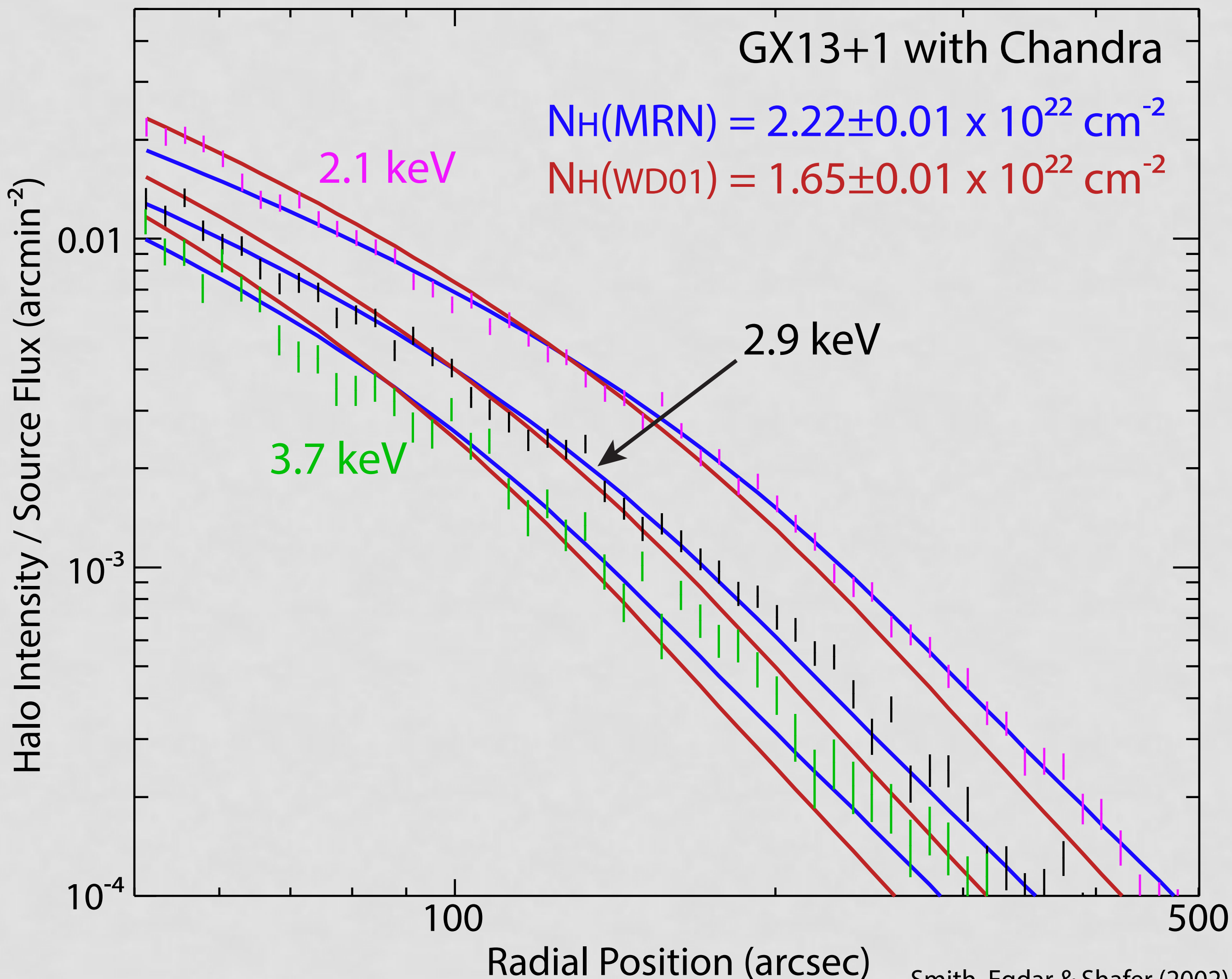
- XMM-Newton observed GX13+1 for 64 ksec in 2017.
- Angular resolution much higher, but data piled-up and unusable within ~50'' of the source due to high count rate.
- Background in CCDs much higher than in ROSAT-type proportional counters.



XMM MOS-2 Observations Of GX13+1

X-RAY HALOS: MODERN

- Can now measure halo as a function of energy
- Fits using smoothly-distributed dust OK, but MRN better than WD01.

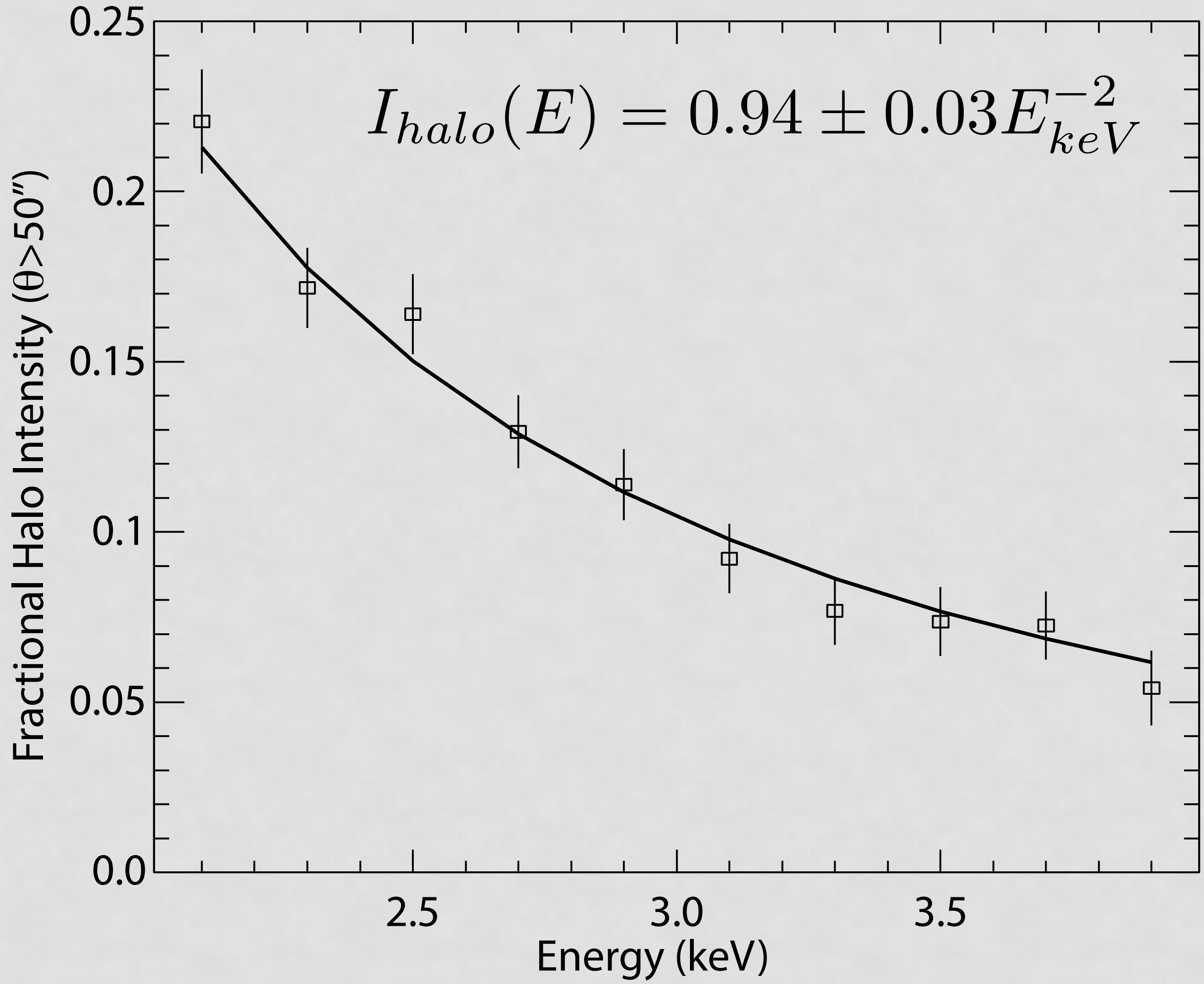


Smith, Egdar & Shafer (2002)

X-RAY HALOS: MODERN

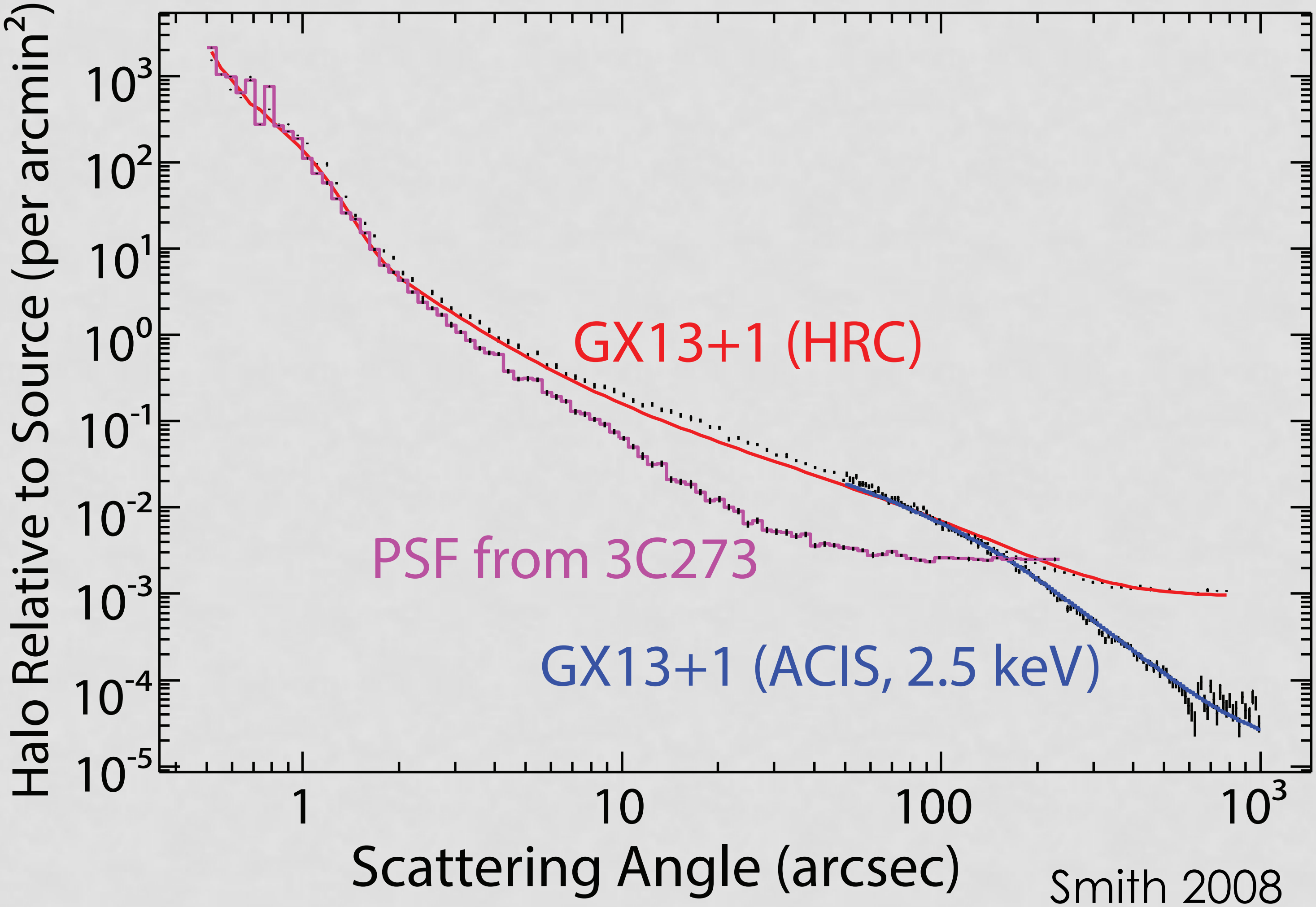
The total scattered fraction between 50-600" fits the E^{-2} scaling predicted from theory well.

Note that this is independent of the dust model/ size distribution.



X-RAY HALOS: MODERN

Can even extend to smaller angles, by giving up energy resolution.



Smith 2008

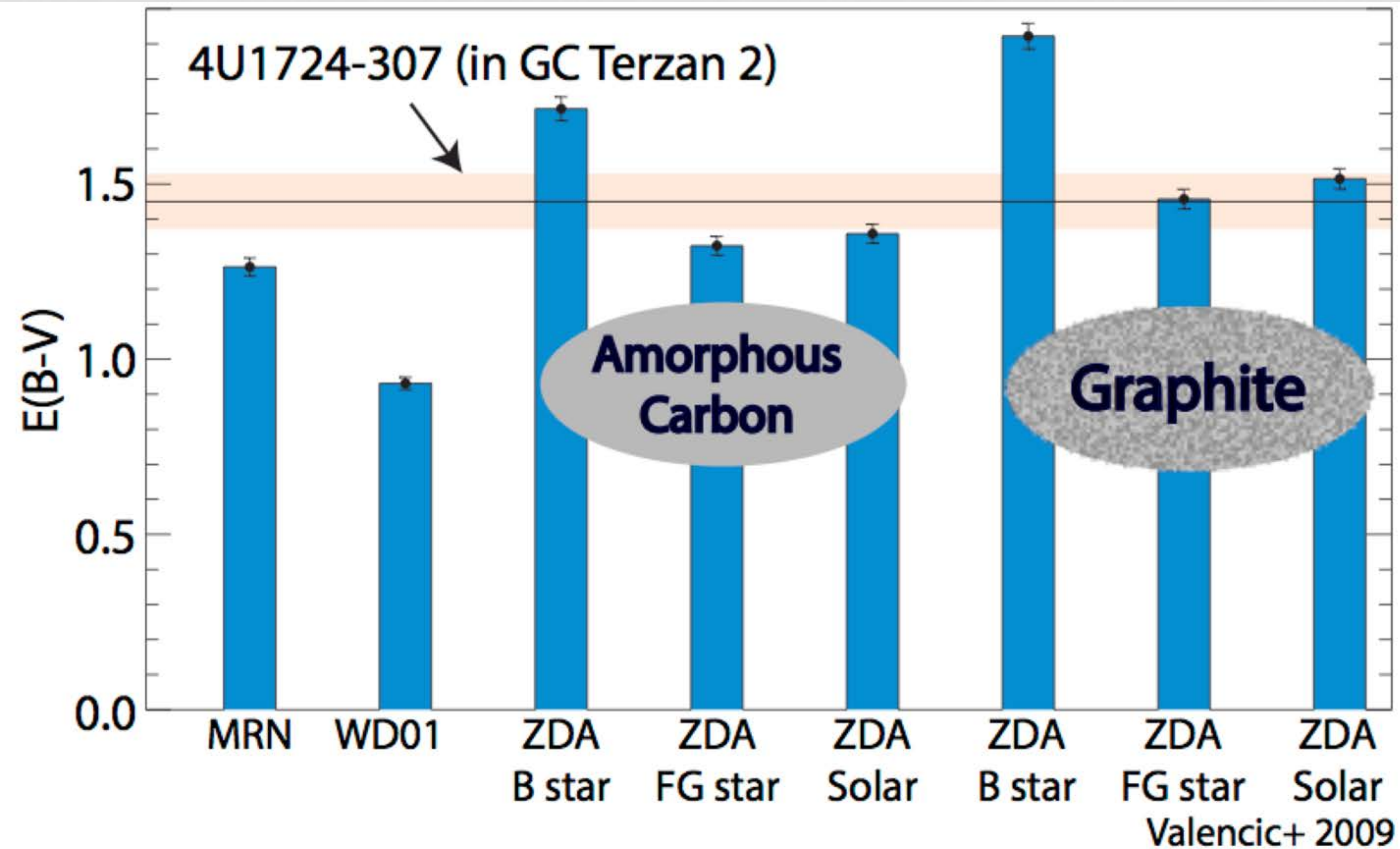
X-RAY HALOS: RESULTS

- **Porosities**: The X-ray halo is proportional to $N_H\ \rho^2_{dust}$. Measuring both a halo and N_H gives the grain density, which is tied into the overall Galactic metallicity.
- **Size Distributions**: X-ray halos are created mostly from large dust grains, so we can put limits on the mass and distribution of grains larger than 0.1μm.
- **Positions**: The shape of the X-ray halo depends on the position of the dust grains along the line of sight, so we can hope to find out if the dust occurs in clumps.
- **Shapes**: Azimuthal variation could tell us about dust shapes.
- **Clouds**: Only X-ray halos and IR observations can see dust in the dense clouds where star formation occurs, and only halo observations can tell us about the size distributions of the large grains in those clouds

TESTING DUST MODELS

- MRN77: Mathis, Rumpl & Nordsieck (1977)
  - Silicate, Graphite dust with PL = 3.5, up to 0.25μm sizes, fit to UV & optical extinction.
- WD01:
  - A range of models, again with separate silicate & graphite, designed to match existing IR, optical, UV data over many sightlines.
- ZDA04:
  - A huge range of models, including some composite grains, designed to fit existing data constrained by known abundances.

TESTING DUST MODELS



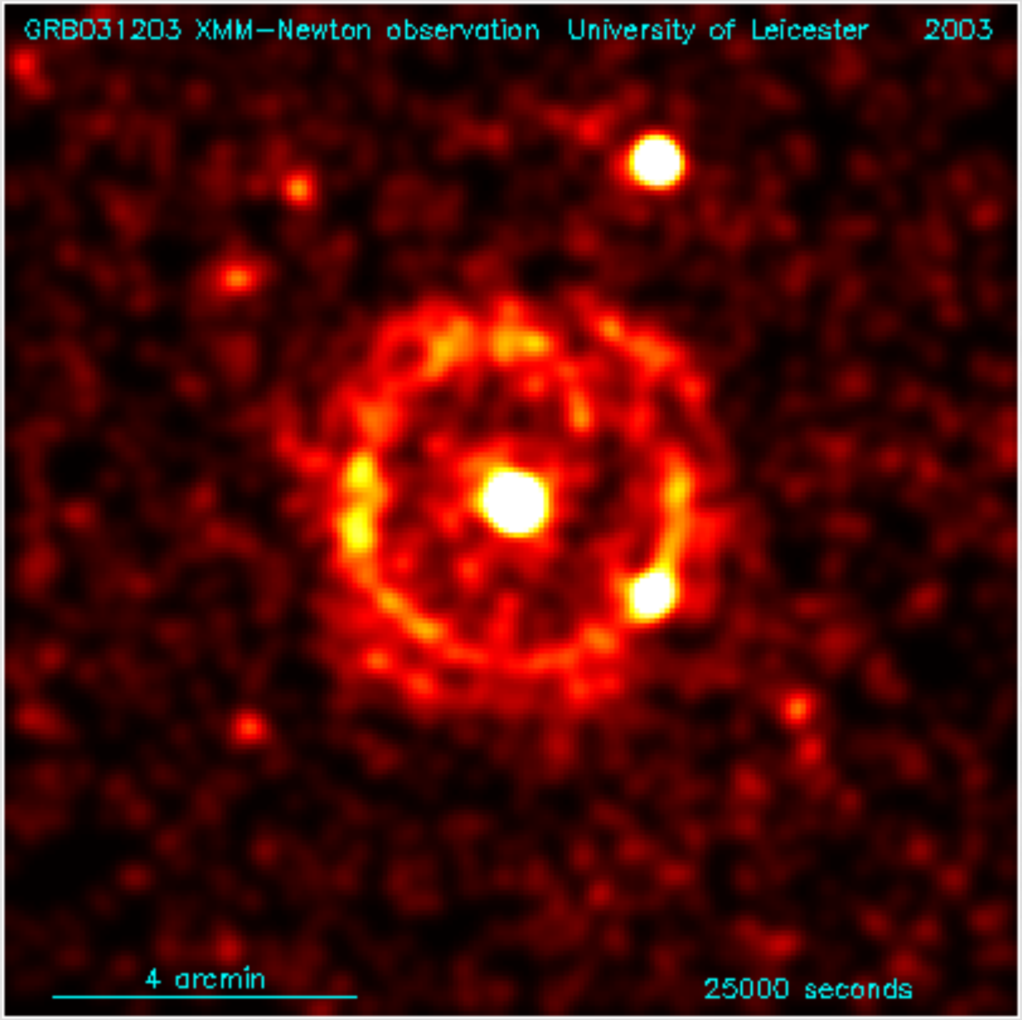
TESTING DUST MODELS

- MRN77: Mathis, Rumpl & Nordsieck (1977)
  - Tends to fit halos well, but A_V or E(B-V) often in poor agreement.
- WD01:
  - Typically provides poor fits, especially compared to MRN, although not unacceptable. A_V or E(B-V) often in poor agreement
- ZDA04:
  - Composite models all but excluded. Models with Bare graphite grains often work better than MRN models; Amorphous Carbon not as well. Abundance constraints not consistent.

Xiang et al 2011
Valencic & Smith 2008
Valencic et al 2009

DUST (AND SOURCE) POSITIONS

- Vaughan et al (2004) used a Gamma-ray Burst 'backlight' to find expanding rings due to dust clouds 880 and 1390 pc distant.
- Vaughan+ 2006 used another GRB, suggested a_{max}~0.5μm for a cloud @140 pc (Ohiuchus?), and τ_{sca}/A_V>0.022



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We have $\frac{d\sigma}{d\Omega}(E, a, \phi)$ To get the observed halo intensity, $I_{\rm halo}(\theta)$ integrate the scattering over the line of sight:

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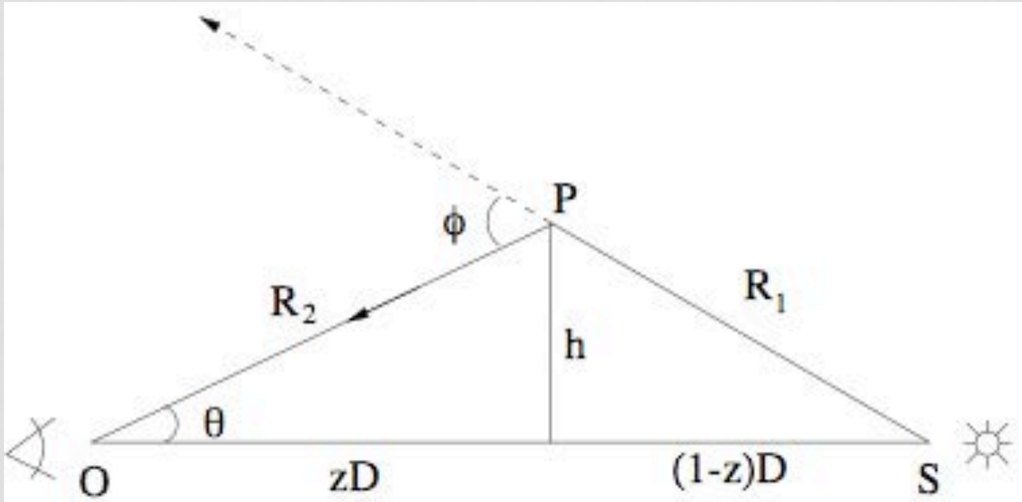
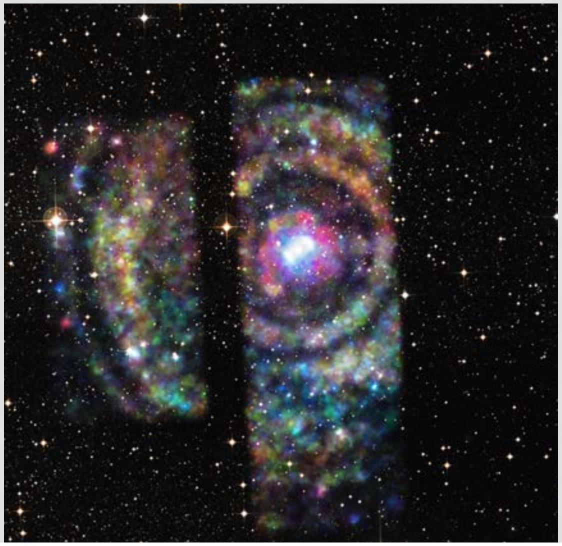


DUST (AND SOURCE) POSITIONS

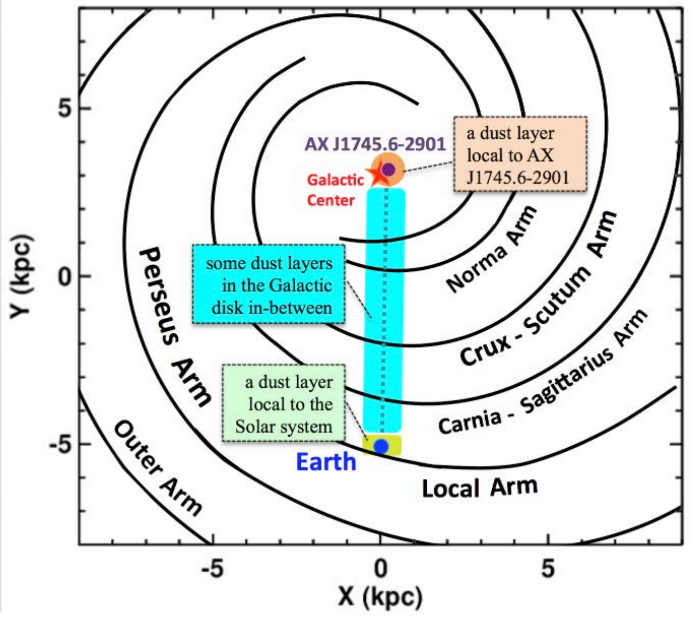
- Svirski+ 2011 measured the distance to SGR 1806−20 of 9.4 – 18.6 kpc (90%), compared to earlier 6−15 kpc
  - Found the dust size PL slope to be 3.3±0.6, and that the dust size distribution extended to 0.1μm.
- Xiang+ 2011 found Cygnus X-1, a black hole candidate, to be 1.81±0.09 kpc (parallax finds 1.86±0.12 kpc).
  - Detailed fits to radial profile favored ZDA04 BARE-GR-S, BARE-GR-FG or a bespoke model.
- Xiang+ 2007 put 4U1624-490 at ~15 kpc, and found that much of the spectral absorption is local.
- Rivera-Ingraham & van Kerkwijk(2010) used halos to measure distances via robust A_V determination.

DUST (AND SOURCE) POSITIONS

- Heinz+ 2015 used a giant burst of Cir X-1 to reveal four dust clouds along the line of sight and measure the distance to be 9.4(+0.8,-1) kpc.



- Jin+ 2017 used the profile and eclipses of LMXB AX J1745.6-2901 (in the Galactic Center) to identify multiple dust clouds and show a significant amount is local, not at the GC

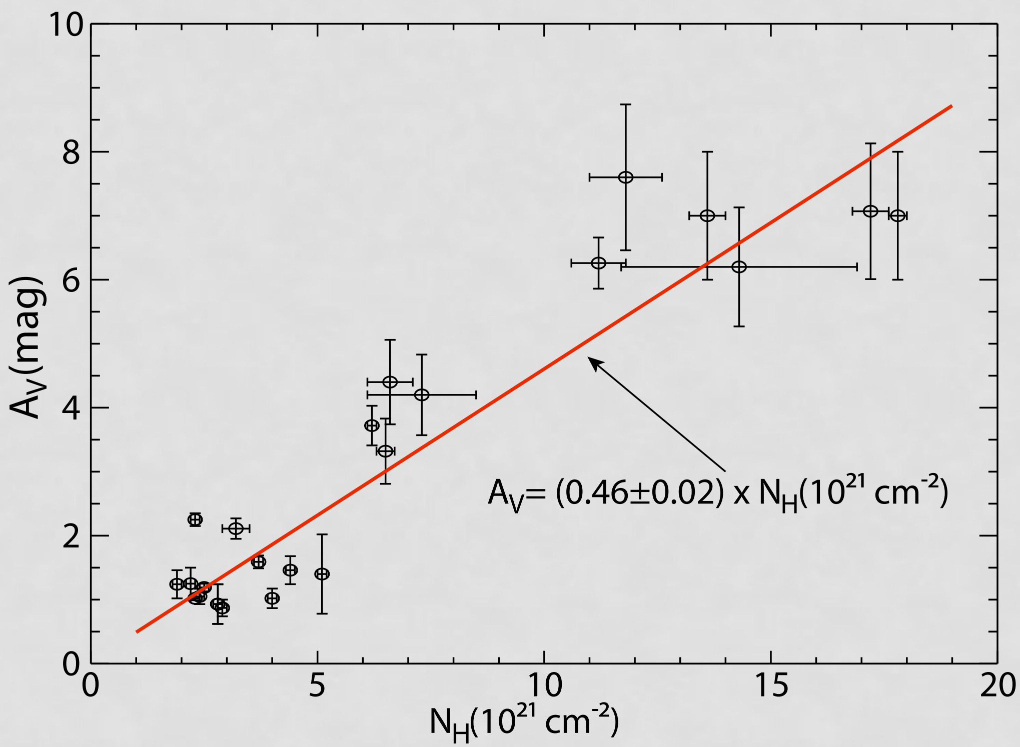


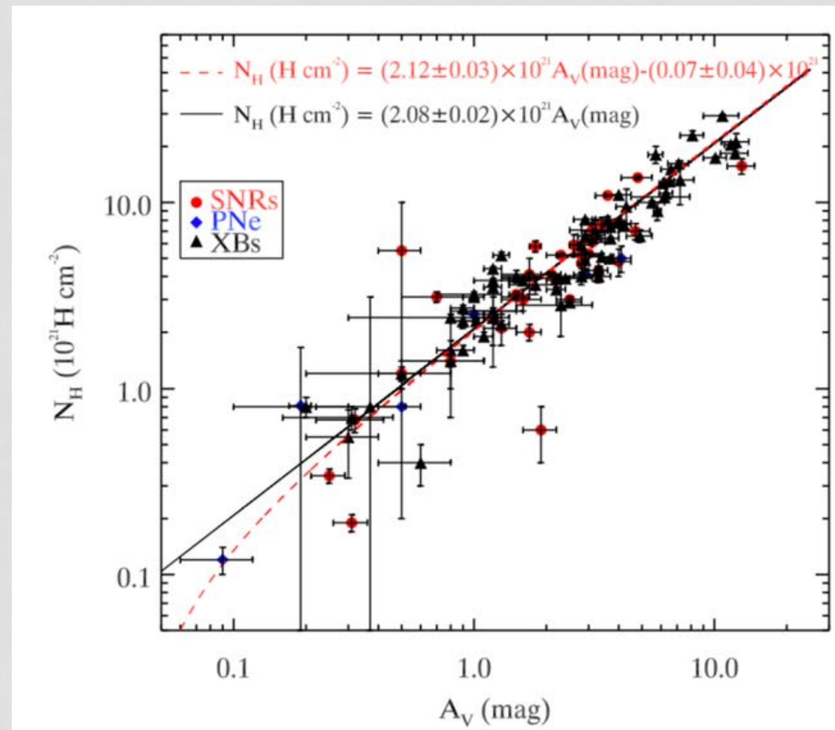
LET'S GET SYSTEMATIC

- The HEASARC data archive was searched for all observations from the XMM-Newton Observatory (EPIC) and Chandra X-Ray Observatory (ACIS):
  - Bright, point-like source in an uncrowded field
  - $N_H > 10^{21}$ cm^{-2}.
- 61 potential X-ray binary sources
  - 49 low-mass, 12 high-mass
- 35 had usable data.
- 28 yielded good fits to their halos
  - low χ^2, realistic N_H & cloud positions

Valencic & Smith (2015)

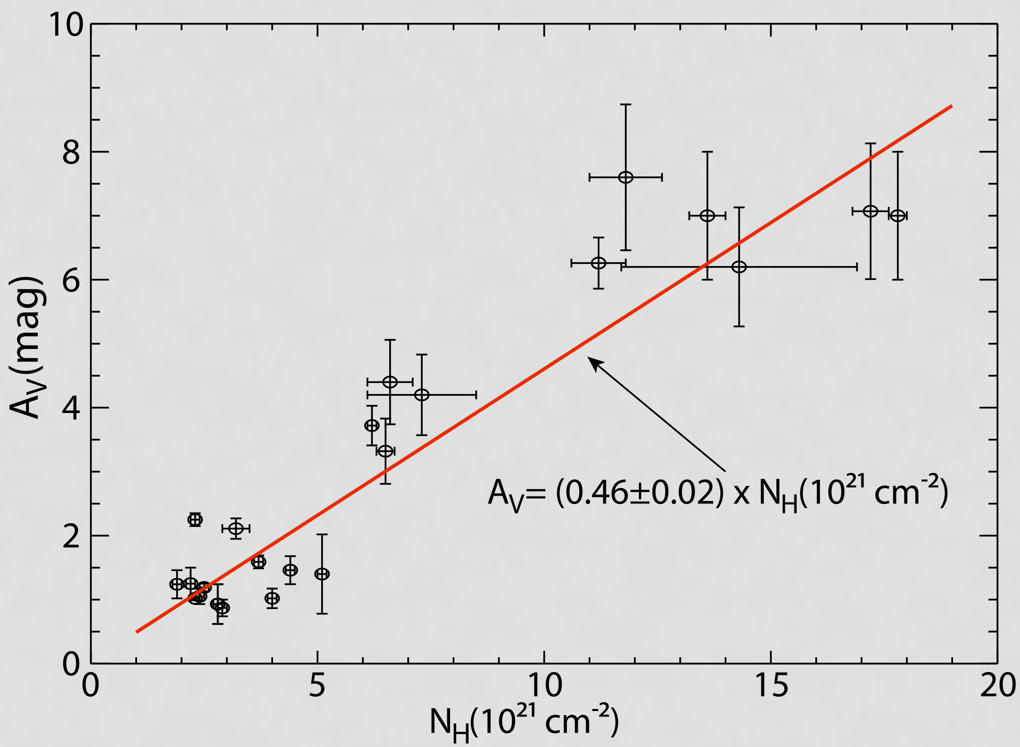
SURVEY RESULTS

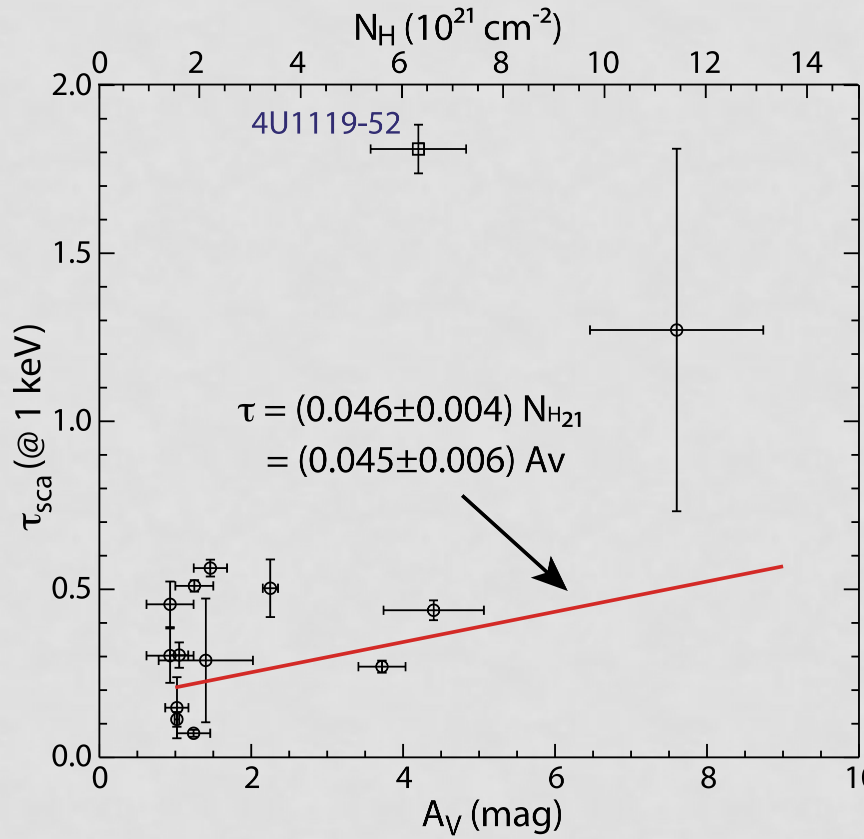




X-ray spectral fit vs A_V gives $N_H/A_V = 2.08\pm0.3$, in excellent agreement with far more complete survey of N_H vs A_V done by Zhu et al 2019 ($N_H/A_V = 2.08\pm0.02$)

SURVEY RESULTS

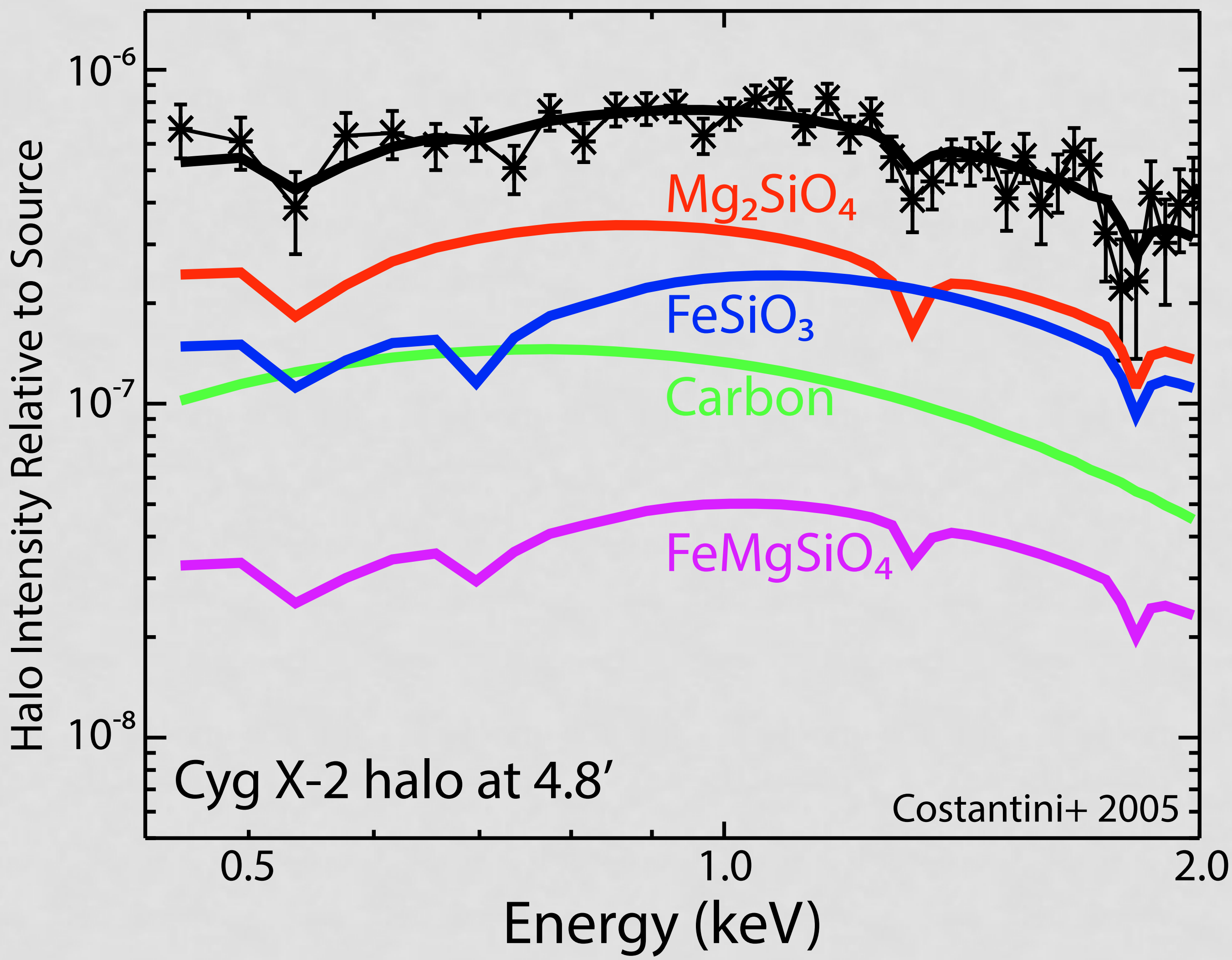




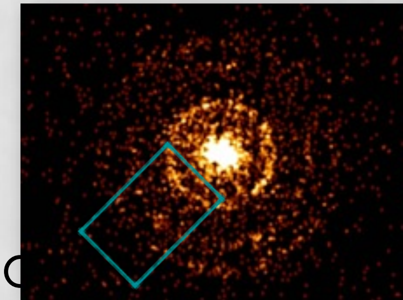
Results directly comparing dust scattering depth, using measured halos, still require work. Compare to τ_{sca}=0.087 x A_V(mag) (Predehl & Schmit 1995)

X-RAY HALOS: FUTURE

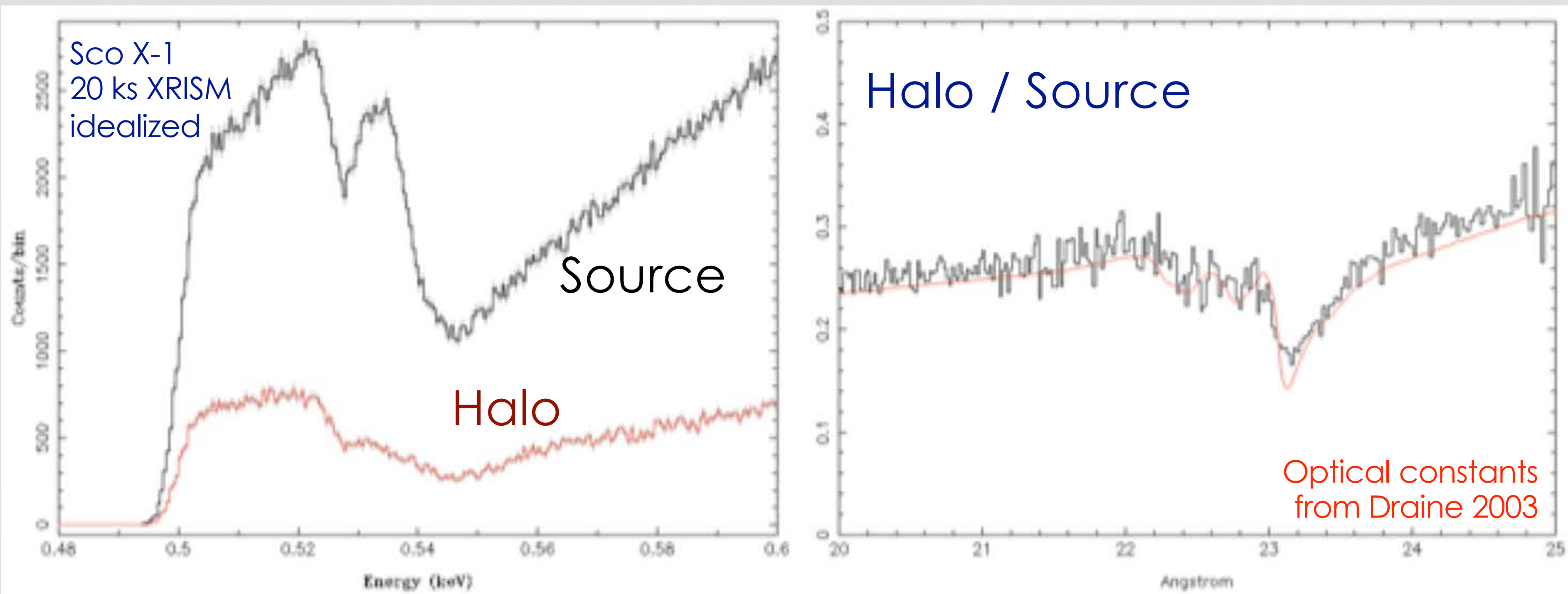
While challenging, XRISM will be able to do this regularly on a range of sources.



Future of Astromineralogy



High resolution X-ray spectroscopic imaging with XARM, Athena, and Lynx will **directly identify constituent dust grain elements** with a high resolution spectrum of dust scattering halo

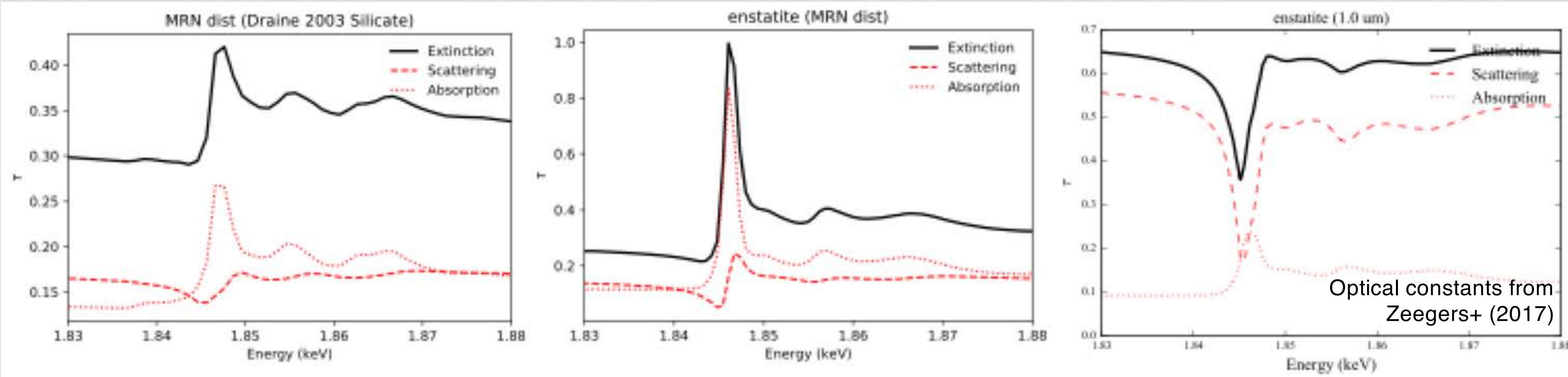


2018 2023 2028 2030+

XRISM ARCUS *Athena* AXIS *Lynx*

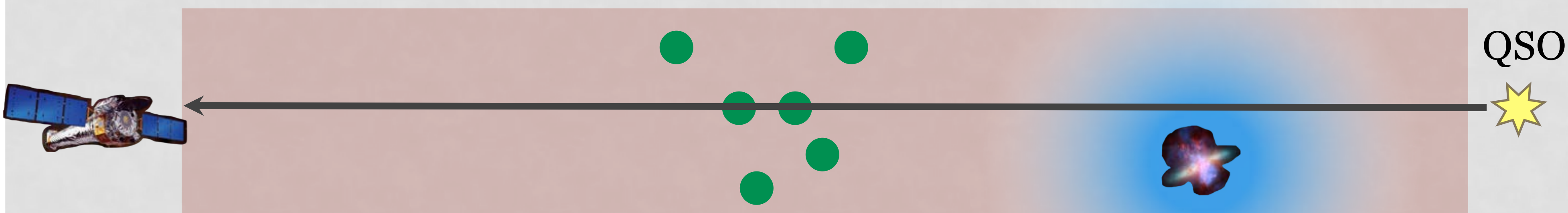
Future of Astromineralogy

Gratings instruments are ideal for high resolution spectra of **soft** X-rays



Mineralogy and **grain size** with photoelectric absorption edge

Probe cold phases of the **most abundant metals (C,O)**



Look at **extragalactic dust** at higher redshift

2018 | 2023 | 2028 | 2030+

XRISM | ARCUS | *Athena* | AXIS | *Lynx*

SUMMARY

- Why X-rays
- X-ray Halos
  - Mechanism, History
  - Results
    - Dust porosity: **Can't be large (< 30–55%)**
    - Dust size distribution: **A few models do fit, but not MRN or WD**.
    - Dust positions: **Can be measured!**
    - Survey: **Promising early results**.
- Future Opportunities